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THE CURRENT STATE OF CORROSION CONTROL: TECHNOLOGIES AND COSTS

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ABSTRACT

Corrosion control has been known both as a cost-saving and as a health protection method for almost a century. But, surprisingly, relatively little field and laboratory research has been conducted contrasting alternative approaches or presenting results before and after such water treatment programs were implemented.

A thorough review of chemical treatment strategies and engineering technologies, a presentation and analysis of field trials, and a summary of costs incurred for various treatment approaches is needed. Unfortunately, the data are far from complete. However, all water systems across the country, public and private, are being required now to address both the health risks of drinking water contaminated by corrosion by-products and the cost-reducing potential of corrosion treatment. This paper presents a snapshot summary of the state of current knowledge about control of internal corrosion, focussing particularly on lead and copper corrosion.

Treatment Approaches for Corrosion Control for Metals

The chemistry of internal corrosion is complicated, but most corrosion problems can be addressed by one of several basic treatment approaches. Because the effect of pH on the solubility of many metals is very strong, most systems can significantly reduce their lead problems by pH adjustment, given no conflicting conditions. Carbonate

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adjustment usually means the addition of carbonate to waters having very low alkalinities; however, high alkalinity waters could need alkalinity removal to lower their corrosivity to lead and copper. Obviously, the optimum carbonate level is associated inseparably with pH. The addition of chemical corrosion inhibitors (such as orthophosphates or silicates) facilitates the formation of passivation films that form on the pipe under the appropriate pH/carbonate conditions. Calcium carbonate saturation resulting in calcium carbonate deposition is widely practiced as a general corrosion control strategy, despite the derth of published studies demonstrating its effectiveness for trace metal control.

Alternative engineering strategies must include consideration of treatment plant and utility size, other water treatment processes implemented, etc., as well as source water characteristics and chemical treatment selection.

Cost of Treatment

Data on the costs of alternative treatments have been assembled from a variety of sources, including articles in the published literature on the corrosion control experience of individual water utilities; descriptions of corrosion control approaches or specific treatments from the experience of the engineering and chemical firms providing those services; typical costs calculated by EPA as part of its regulatory support activities; and a survey of costs actually incurred by some public water systems currently conducting corrosion control activities. Cost curves developed previously have been updated to reflect current conditions. Data on two sample approaches are presented: pH and alkalinity adjustment through the addition of lime and use of zinc orthophosphate as a corrosion inhibitor. In general, zinc orthophosphate is a more expensive treatment but considerably less expensive formulations of the chemical are available than the particular form costed here. Both treatments show economies of scale and both show increased costs associated with higher dosages.

Comparing the Costs and the Benefits

The benefits of corrosion control treatment include benefits to water utilities, consumers and society as a whole. Some analyses of materials damage benefits are presented.

INTRODUCTION

The first paper suggesting that water treatment could reduce lead corrosion and thereby reduce consumers' excessive exposure to lead was in 1920 (1). This followed several warnings during the second half of the 19th century in New England, Germany, and elsewhere on the dangers of lead pipes and resulting plumbism (2,3). Little was written in the 50 years from then until about 1970 when interest in centralized

corrosion control treatment re-emerged. Numerous papers throughout the world have appeared, describing alternative treatments, pilot studies, system experiences, monitoring protocols, etc., addressing lead contamination of drinking water and the electrochemical phenomenon -- corrosion -- that is its principal cause.

While some utilities have initiated corrosion control activities out of concern for public health, most efforts have resulted from a more pragmatic consideration: corrosion costs money. Several approaches to corrosion control are possible. The decisions on what approach to employ call for an evaluation of water quality, plant size, other treatments already begun, system configuration, and, of course, costs.

TREATMENT APPROACHES FOR CORROSION CONTROL FOR METALS

"Corrosion control" can mean many things. Most often it means reducing premature plumbing failures and lengthening the service life of pipes and other plumbing components. However, it also includes maintaining good water flow characteristics in distribution mains by reducing tuberculation, avoiding aesthetic degradation from corrosion by-products (e.g., avoiding "red water" and staining), reducing negative industrial or commercial impacts from unwanted metals concentrations in the water; reduction of metal loading of wastewater treatment plants; and reducing adverse health effects from toxic corrosion by-products (e.g., lead, cadmium and high levels of copper). The strategy to be used in treating water for corrosion control is dictated by the perspective.

At the broadest level, alternative strategies could be:

- The removal or reduction in concentration of a corrosion-causing water constituent (such as chloride, chlorine, dissolved inorganic carbon (DIC), or dissolved oxygen)

- The adjustment of general water chemical characteristics to reduce the corrosivity of the water, or to promote the development of protective surficial pipe films (such as adjustment of pH, alkalinity, or hardness)

- The addition of chemicals to control the causes of aesthetic complaints (such as the addition of polyphosphate sequestering agents to control red water complaints)

- The addition of chemicals ("inhibitors") to promote the formation of either protective barrier films that can change the form of corrosion (eg. change pitting to uniform dissolution or reduce tuberculation), reduce the corrosive attack on the pipe (such as zinc-containing coatings on A/C pipe or silicate barrier films on galvanized pipe), or to form films that tie up the corrosion by-product so that it is not released into the

water (such as the formation of lead orthophosphate films on lead pipe)

Because the different materials in contact with the water can respond differently, no single approach to optimally solve the diversity of internal corrosion problems is currently possible. Also, inherent characteristics of the water (such as hardness and alkalinity) may themselves limit the corrosion control strategies that can be employed in different systems.

The processes related to the plumbosolvency of lead pipes are better understood than those related to the corrosion or dissolution of lead:tin solder, brass or bronze. In the latter three cases, corrosion is also related to galvanic coupling within and between materials, and the amount of lead available for dissolution may change over time, complicating the situation further.

Treatment Chemicals

Many different chemicals are available for adjusting the general water quality or providing chemical components that can act as corrosion inhibitors or sequestering agents. Table 1 lists some of these chemicals and their general application. Some chemicals, such as the polyphosphates, silicates, and some of the zinc orthophosphate formulations, are available in different chemical compositions (such as Zn:P ratios, Na:Si ratios, or type of polyphosphate) from different manufacturers. The dosages necessary of components of these formulations may influence which compound a particular utility should purchase.

Table 1 includes several "generic" chemicals that are potentially useful and economical sources of orthophosphate, when the synergistic effect of zinc is not necessary or when other side-effects of zinc (wastewater concentration, etc.) should be avoided. The use of these sodium salts, or phosphoric acid, is common in Europe, and has been applied successfully to lead control programs in Great Britain and Scotland (3, 15), and in galvanized pipe corrosion treatment in Germany (3). There are no AWWA standards for the purchase of orthophosphates. However, they can be purchased from many chemical distributors by specifying a food grade chemical, ones that meet the National Academy of Sciences Codex for being free of toxic substances, or that meet the National Sanitation Foundation Listings for Health Effects of Drinking Water Additives under Standard 60 (18).

For adjusting the general water quality, ie., pH, alkalinity or hardness, several chemicals are potentially useful. Selection decisions should consider the costs of the chemicals at the required dosages. Table 2 summarizes the qualitative effect on pH, alkalinity, and hardness, of the treatment chemicals listed in Table 1. The amount of each change depends on the dosage and the background water quality (ie., initial

hardness, buffer capacity, pH, etc.). The quantitative aspects of the impact on hardness, alkalinity, and DIC of several of these chemicals are developed in detail (24). Calcium oxide (quicklime), calcium hydroxide (hydrated lime), and limestone (calcium carbonate) can all neutralize acidic waters and add hardness. Limestone is sparingly soluble and is normally only used in crushed form in contactors. Both hydrated lime and quicklime add hydroxide alkalinity, but they do not affect the DIC concentration unless calcium carbonate solubility is exceeded. For large systems (approximately > 10 MGD), lime is usually the economical choice for neutralization or pH adjustment, unless the water is hard and has a high alkalinity.

Large systems usually gravity-feed the chemical slurry into the raw water. Their lime feed systems are normally comprised of bulk storage, dry feeders, and slakers. Smaller systems usually avoid the processing complexity of the slaking by purchasing hydrated lime.

When pH adjustment is desired, and additional calcium is unnecessary, caustic soda (sodium hydroxide) may be chosen. Sodium hydroxide feed systems generally consist of bulk storage of a 50% solution for direct feed using a metering pump. System operation and maintenance are usually much less than with the lime chemicals, so despite the relative danger in handling the caustic, many smaller systems prefer it for pH adjustment. Sodium bicarbonate is a pulverized powder, typically known as "baking soda." In addition to providing a limited amount of pH adjustment ability, it is also an economical source of DIC for pH's below approximately 8.5. Feed systems usually consist of bulk chemical storage, dry chemical feeders, mixing tanks, and metering pumps. Sodium carbonate (soda ash) is more efficient in raising the pH than sodium bicarbonate, and also adds DIC and buffering capacity at a potentially higher pH. The feed systems are essentially the same as those required for sodium bicarbonate.

Two general classes of phosphates exist, which should not be confused. The orthophosphates are comprised of simple salts containing the PO_4^{3-} group, with varying amounts of hydrogen, sodium or potassium. They can be purchased as these salts (Table 1), or can be formed by a combination of soda ash or caustic soda with phosphoric acid, because the active form of the phosphate group (ie., $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) depends upon pH, and the salts dissolve completely in water in concentrations normally used. The selection of the form of the salt (mono-, di-, or trisodium, for example) can also be made on the basis of the pH range of the water in which it will be used, so that the pH will not be affected as it would be with the addition of an acidic formulation.

Commercial zinc orthophosphate dry formulations are available that are essentially blends of different ratios of zinc sulfate with monosodium orthophosphate. Liquid solutions are also available, in

which some sulfuric or phosphoric acid is used to enhance the solubility of the zinc. Feed systems for the granular forms of the orthophosphates normally consist of bulk chemical storage, dry chemical feeders, mixing tanks to form aqueous solutions, and metering pumps. The liquid forms may be added directly via metering pumps.

A broad spectrum of polyphosphate chemicals exist, including tripoly-phosphates, hexametaphosphates, and bimetallic phosphates. These chemicals are mostly used in threshold treatment to limit calcium carbonate deposition, to sequester iron to limit red water complaints, and to limit or reduce tuberculation in iron or steel mains. Except to the extent that they can revert (hydrolyze) to form orthophosphate, they have not been found to be useful in reducing copper, lead or zinc solubility.

Tripolyphosphate and sodium hexametaphosphate can be purchased using AWWA standards. Tripolyphosphates are available in powder or granular form of various densities. Sodium hexametaphosphates, sometimes called "glassy" phosphates, can be purchased as plates, flakes, granular, lump, beads, and as a powder. These chemicals are usually dissolved in water and injected as aqueous solutions, although some of the slowly-dissolving plates are used in contactors. Bimetallic phosphates are less soluble than the other polyphosphates, and because they are usually provided as acidic solutions, they require stainless steel or plastic tanks, pumps, and valves. They come in different Zn:P ratios, solubilities, reversion, and inhibitor (or sequestering) properties. Blends of orthophosphates and polyphosphates are sometimes used to combine corrosion protection (film formation) with hardness stabilization (3).

Sodium silicate is manufactured as a dry chemical (sometimes called "water glass") and as a liquid solution. The ratio of $Na_2O:SiO_2$ varies with different formulations and plays an important role in selecting the proper solution or compound for a particular corrosion control need. The dry granular form is often used in "point of use" hot water systems, through addition by "pot feeders". The cost of silicates is generally higher than that of various types of phosphates, which is one reason why their use is not as common.

Orthophosphate/polyphosphate/silicate blends have been used in Germany for several years to control many types of corrosion (3).

For the control of asbestos-cement pipe corrosion, zinc chloride or zinc sulfate may be useful (25, 26). These chemicals may be purchased and applied to the water with the same considerations as the generic orthophosphate salts, but using the zinc concentration as the parameter of interest.

Treatment Strategies

The most common approach to reducing corrosivity is the attempt to maintain calcium carbonate saturation in the water system or to raise the pH and alkalinity in soft waters from which the formation of protective $CaCO_3$ films would be more difficult. The solubilities of copper, lead, and zinc are all very pH-dependent, so increasing pH through the addition of caustic soda, lime, or hydrated lime is often a useful strategy (3, 23). One drawback is that the pH necessary to control the trace metal leaching, particularly of lead, may be higher than is desired from considerations of disinfection efficiency or calcium carbonate saturation. Another drawback is that iron corrosion is complicated and may not necessarily benefit from pH adjustment without adjustment of other parameters (such as hardness and alkalinity) into ranges that are less than optimum or even detrimental to other metals (3, 27).

It is not clear that the same principles of solubility control apply to lead:tin solder, or lead in brass, that apply to lead pipe. However, there is evidence that pH control is a key factor in both cases (22).

Because pH and alkalinity are interrelated, all waters that have low pH values do not necessarily need DIC supplementation, in the form of sodium carbonate or sodium bicarbonate addition. The DIC must be computed initially, or the alkalinity must be computed for the conditions after the pH change before carbonate supplementation can be determined to be necessary. Considerable research into copper and lead corrosion indicate that while some carbonate (DIC) is necessary to form protective basic carbonate passivation films on the pipes, the solubilities of both metals can increase when DIC is added (alkalinity is increased) beyond a certain critical level at a given pH (3, 21).

Calcium carbonate saturation through the adjustment of pH, alkalinity (DIC) and hardness, is largely effective in corrosion control for iron, steel, and galvanized pipe because mixed calcium+metal carbonates tend to form, to reduce the oxidation rate and to inhibit metal release into the water. For this strategy to work with lead, however, the entire interior surface of the pipe must be covered with a uniform $CaCO_3$ coating to seal the surface. Maintaining such a water chemistry throughout a system without causing scaling problems or lead leaching resulting from high DIC is difficult.

Chemical inhibitors for lead corrosion are generally restricted to zinc orthophosphate formulations, phosphoric acid, or the sodium (or potassium) orthophosphate salts. The use of orthophosphate to control lead corrosion has been demonstrated in a variety of field studies in Great Britain (3, 19, 20). In those studies, the added chemicals were phosphoric acid or the generic salts.

The action of the orthophosphate appears to be from the formation of a surface deposit of sparingly soluble hydroxypyromorphite or possibly tertiary lead orthophosphate as a result of the reaction of lead from the pipe with the orthophosphate in the water (3, 19, 20, 22). The solubility of both of these solids depends greatly upon the pH, DIC, and orthophosphate concentration in the water. Generally, higher orthophosphate dosages are required for higher DIC levels, and the pH for the best performance tends to decrease as DIC increases. Although not precisely quantified, the best pH range for orthophosphate inhibition for lead appears to be approximately 7.2 to 8.2 (depending on DIC and dosage). Considering of the solubility chemistry of these compounds, orthophosphate treatment programs, such as that attempted in Boston in the late 1970's, must include proper DIC and pH control to succeed (3, 22, 23). The pH in that study was much lower than the minimum necessary to form a lead orthophosphate film at the system pH and alkalinity.

Orthophosphate also provides an effective means of reducing galvanized pipe corrosion, because the pipe surface can be protected by a film of $Zn_3(PO_4)_2{\cdot}4H_2O$, or similar solid (3, 23, 26). Formulations of orthophosphate including zinc have been shown to reduce the corrosion of iron and steel pipe in several studies and in asbestos-cement pipe (3, 25, 26).

The addition of silicates for corrosion control in drinking water distribution systems has not been studied to the extent of the other strategies. The effectiveness of the silicates themselves has sometimes been difficult to separate from the role of the pH adjustment that usually must accompany their use. Silicates apparently work by reacting with existing corrosion deposits, particularly basic carbonates such as hydrozincite, to form a more uniform and impermeable film. Silicates have not been found to be especially useful for the control of lead corrosion, but several studies have found them useful for galvanized pipe, copper lines, and distribution mains, both alone and blended with phosphates (3, 18, 28).

One common consideration for all inhibitor programs is that the reactions that form the passivating films on the pipe are reversible, so continous maintenance dosages are required to keep the films on the pipe from redissolving.

Only certain corrosion-causing substances can be easily removed. Reducing DIC through air-stripping of CO_2 is an effective, if complicated, approach to lowering the aggressiveness of some waters to lead and copper. For some hard waters, in which undesirably high DIC levels are also present, air-stripping can produce calcium carbonate precipitation unless it is done at a sufficiently low pH. Because hard waters usually have a considerable buffering capacity, lowering the pH

through acid addition to achieve good stripping efficiency, and then readjusting the pH upwards can entail considerable chemical and operational expense.

Reducing chlorine dosage when possible will generally slow the rate of copper corrosion. While conversion from chlorine to choloramines has been frequently suggested as another means of reducing water corrosivity, there are some indications that chloramines might increase copper or lead levels in the water (21, 29).

Finally, there are ways to reduce corrosion potential that are not chemical treatments, but include other actions the utility can take to control factors contributing to corrosion. Among these are meticulous attention to maintaining uniform water quality, maintaining constant water pressure, eliminating 'dead ends' in the distribution system, reducing water turbulence, good design of the system and attention to the materials used in the system. The choice of materials can enhance or inhibit corrosion rates due to the added electrochemical activity associated with contact between materials with different nobilities.

COSTS OF TREATMENTS

In this paper, we present costs to the water utility for 2 commonly-used sample treatment approaches as a method for raising methodological issues and for presenting a framework for decision making in this area: pH and alkalinity adjustment through the addition of lime, and use of zinc orthophosphate as a corrosion inhibitor. These 2 approaches were chosen to present one relatively inexpensive chemical (lime) and are relatively expensive chemical (zinc orthophosphate). The cost data rely upon standardized cost curves developed by EPA in 1979, updated to reflect current costs. All monetary estimates are presented in 1988 dollars, for 3 size categories of treatment plant: 1, 10 and 100 mgd. We also assumed average consumption of 300 gallons per household per day and that a 1 mgd system serves 3,300 households, a 10 mgd system serves 33,000 households, etc.

These cost estimates should be understood as examples only. Costs will vary greatly from system to system based upon local conditions such as existing facilities and in-place treatment, cost and availability of labor and capital, age and configuration of system, and, of cours, water quality. For reasons discussed below, these estimates are probably conservative and actual costs are likely to be somewhat lower.

Neither the addition of lime nor of zinc orthophosphate is effective or appropriate in all circumstances. Both are more effective in some circumstances than others. Water quality is probably the most important consideration. Some of the factors that will determine the

likely efficacy of a particular treatment are summarized in the treatment approaches section of this paper.

Costs are calculated separately for capital vs. operation and maintenance (O&M). Both were developed for lime and zinc orthophosphate feed systems that use feed rates of up to 10,000 lb/hour. Dosage ratios estimated are 5, 10, and 15 mg/l for lime, and 0.5, 3, and 5 mg/l for zinc orthophosphate.

Construction costs and operating and maintenance costs rely upon previously published results (12), updated to 1988 dollars. Process energy requirements are for the feeder and other equipment are based on motor sizes for the various equipment (12). Annual maintenance material costs were based on 3% of manufactured equipment costs, excluding the cost of the storage hopper. Chemical costs are not included in the maintenance material costs presented in the curves but are included in the O&M estimates in the summary tables. The cost of lime was assumed as $0.04/lb and the zinc orthophosphate as $2.55/lb.

Annualized capital costs assume a 20-year amortization of costs at 6% and are based upon estimates of incremental expenditures to install corrosion treatment on existing plants. While the actual service lifetime of a treatment plant is probably closer to 50 years (or even greater) than to 20 years, business costs are often presented amortized conservatively (and for tax purposes) over only 20 years. This means that capital, and hence total, costs are overestimated. For comparison, a recent American Water Works Association Research Foundation report (18) based similar cost estimates assuming service lives of plumbing components and capital at 75 years.

Cost estimates are presented in Tables 3 for lime treatment and 4 for zinc orthophosphate. As can be seen in these tables, there is a different balance between capital and O&M costs for the 2 alternative treatments. Annual lime addition costs are more moderate in total and, except for 2 cases, capital and O&M costs are within a few factors of each other. On the other hand, the total annual costs for treatment with zinc orthophosphate are much higher, and the O&M costs are generally an order of magnitude or more higher than the capital costs. However, different utilities have a different ability to pass through operating expenses in their rate structures or to raise funds for capital improvements; these considerations will also affect the choice of treatment. The costs of treatment are greatly influenced by dosage rate and both alternatives evidence economies of scale.

Figure 1 shows the unit costs for both lime and zinc orthophosphate treat-ment in ¢/1000 gallons of water versus system size. As can be seen, lime treatment exhibits much greater economies of scale than does treatment with zinc orthophosphate. Total costs differ greatly also.

Note that zinc orthophosphate is a relatively expensive chemical for use as a corrosion inhibitor. It is likely that other chemicals, for instance "generic orthophosphates, may cost half or less of the cost of zinc orthophosphate. Utilities considering corrosion inhibitors should price the available chemicals; a partial list is included in the treatment section of this paper.

Another way to compare these 2 sample treatments (and particularly useful for comparison with alternatives using different discount periods) is to calculate the net present value of total expenditures over a fixed time period for the alternatives. Present value analysis permits an evaluation of the full stream of expenditures as opposed to estimating annualized costs. Our present value estimates are based upon the same annualized capital and O&M costs presented in Tables 3 and 4. Because both alternative corrosion treatments presented in this paper use the same discount period (20 years) and the same discount rate (6%), this calculation presents no new data for costing analysis but can be used in the next section for comparison with estimated benefits. Table 5 presents net present values for lime addition and Table 6 presents the data for the addition of zinc orthophosphate.

COMPARING THE COSTS AND THE BENEFITS

Corrosion damage costs money, but so does corrosion control. Corrosion can occur at the treatment plant, throughout the distribution system, and in household plumbing. Wherever it occurs, it has effects that cost both utilities and consumers money. Corrosion results in pipe breaks and leaks; in damage to water meters, plumbing components and storage facilities; in excessive repair and replacement increasing both operating and capital expenses; and in water loss. Estimates of the total annual costs of corrosion damage incurred by water utilities have ranged from $1.7 billion (4) to up to 25% of total annual operating costs (5), which has been estimated at about $5 billion (6). Estimates of the costs of corrosion damage to consumers range from roughly equal the costs to utilities (7) to double the utility costs (8).

How much of this damage is avoidable and how to decide how much to spend on corrosion control are decisions facing each water utility separately.

There are several methods for comparing the costs and benefits of a particular action. In general, the costs are more easily quantified than the benefits. Cost uncertainties relate primarily to general business uncertainties: Will the market grow or contract over the time period considered? How long will the machinery last? What will happen to the cost of money? Will the relevant laws change? etc.

The benefits, on the other hand, are usually quite difficult to calculate and, to our knowledge, no benefit analysis has ever been done that attempted (or claimed) to estimate all the benefits associated with a specific action. Benefits usually include improved health and welfare, public goods, decreased environmental damage, and the like; obviously, all are difficult to describe even qualitatively and quantitative estimates are often virtually impossible.

Nonetheless, decisions must be made on many issues, including whether and how much corrosion control treatment should be installed. In this section, we present several alternative, largely complementary, methods for comparison and as aids in decision-making.

None of the methods incorporates all the benefits of installing corrosion control treatment. Probably the largest single category -- health effects -- is not included here at all, although it has been addressed at least in part elsewhere (9). The only category of benefits included here relates to "materials damages avoided"; that is, reduced damage to the physical components of the public and private plumbing systems and related operating, maintenance and labor costs. Even within this single category, relatively few elements are included. Therefore, these estimates of benefits should be understood as conservative, incomplete and undervalued.

Because the cost estimates are also estimated conservatively (i.e., actual costs are likely to be lower), the derived benefit to cost ratios are presented as lower bound estimates.

Likely Effect of Corrosion Control Treatment

Several studies have attempted to estimate the likely effect of corrosion control treatment. For instance, in the late 1970s, a study conducted by the City of Seattle Water Department and Kennedy Engineers found that raising pH and alkalinity were cost effective in reducing plumbing system maintenance costs for the utility (13). They found a benefit to cost ratio of greater than 5:1 and further estimated that benefits for consumers could be an order of magnitude greater.

An earlier EPA study summarized much of the literature on estimates of the amount of corrosion damage that was avoidable through corrosion control treatment (9). A summary table from that report is produced here as Table 7. As can be seen, published estimates of avoidable damage range from 20% to 50% of total damage. For comparison, other studies based on the actual experience of utilities implementing water treatment have found their efforts rewarded by reductions in corrosion rates of 70-80%, averaged over a 5-6 year period (14). An intermediate estimate is provided by field and laboratory data from Great Britain, where raising pH from 7 to about 8.5, within the alkalinity range typical of the U.S. (about 10-200 mg/l as $CaCO_3$)

reduced the solubility of lead carbonate by 40-75% (15). Estimates for the city of Seattle predicted a reduction of 30-75% in corrosion rates (13, 30). Another British study also estimated that for the relatively corrosive waters typical of the U.K., raising pH from below 6.8 to over 7.2 could reduce average lead levels in water (related to but not identical with corrosion rates) by about 75% (16). It is likely that the more corrosive the water, the greater the benefits of corrosion control will be.

More recently, an American Water Works Association Research Foundation report (18) has summarized the data on reductions in internal corrosion rates for iron, copper and zinc that have actually been documented by utilities practicing corrosion control. That report found that corrosion of iron was the most difficult to control, but that rates could be reduced by 20-50% in both laboratory and field trials. Corrosion rates for copper and zinc were documented to have been reduced by 65-85% and 45-70%, respectively, by the surveyed utilities. Overall, this report assumes reductions of 25-50% are likely to occur. Of course, the report clearly states that reductions will vary greatly on a utility by utility basis.

Capital investment in water supply has averaged $5 billion (1988 dollars) a year for the last decade or so, and annual operating and maintenance expenses also amount to roughly $5 billion (1988 dollars) each year (6). Table 8 shows the relative annual costs associated with various municipal water supply functions. As can be seen, transmission and distribution account for the largest percentage of capital investment and a significant portion of the operating cost investment. Distribution system functions can often account for 80% of the total expenditure in municipal drinking water systems. A reduction in any of these categories, but especially in repair or replacement affecting either operating or capital costs (or both) for transmission and distribution of water could save utilities significant expenditures.

For consumers, the major "materials" benefit is probably extended service life for plumbing components (pipes, hot water heaters, radiators, faucets, etc.) and reduced visits from plumbers. In addition, the consumer may realize health benefits associated with decreased exposure to metals (9). When benefits accrue to the water utility, the consumer may also enjoy reduced water rates.

Some other potential benefits from a corrosion control program include reduced metal loading to wastewater treament plants, less wasting of water from flushing contaminated water, decreased staining of fixtures and clothing, reduced metallic taste, and decreased use of bottled water and point-of-use devices by consumers.

Distribution System Benefits

In 1985, U.S. EPA and the American Water Works Association Research Foundation initiated a study to determine the factors influencing repair rates for distribution system components (10). Among the data collected in that study were repair rates for several utilities, presented in Table 9. As can be seen, repair rates vary greatly among systems. Calculated averages, consequently, do not represent the estimated benefits to a specific utility but, rather, the mid-point of the range of estimated benefits for all systems.

More detailed analysis shows that pipe breaks and leaks requiring repair vary by part of pipe (joint, circumferential, hole-blowout, etc.) and by pipe diameter. Surveying only 6" pipes, a repair event history was developed for each pipe. This inventory shows evidence that after the first repair, the period to the next repair is shorter than the time period from installation to first repair and that, thereafter, the time to each subsequent repair becomes increasingly short. For instance, data from Cincinnati, Ohio and New Haven, Connecticut show that, while average times for installation to first repair were 15 years for Cincinnati and 22 years for New Haven, average times from first repair to second were 5 and 10 years, second to third repairs were 2.5 and 5 years, etc. Extending the period from installation to first repair, then, likely has cascading effects through the service lifetime of the individual pipes and, hence, the system.

Given the scale of total investment in water system capital and annual O&M costs, extending the life of pipes by even 5% or 10%, let alone the 20-40% that is probably more likely, would produce significant benefits to the water utility and the rate-paying public. We used previously published cost functions for projecting average total capital investiture, annualized capital costs and O&M (11), for 1 mgd, 10 mgd, and 100 mgd plants, assuming 50 year amortization of capital by system at 6%, to produce the estimated distribution system costs in Table 10.

Exending the average lifetime of the distribution system by increments of 5% provides the system benefits summarized in Table 11. These estimated annualized costs should be compared to the annualized costs in Table 10, e.g. treatment producing a 5% reduction corrosion damage to the system will reduce annual capital and O&M costs for a 1 mgd plant from $347,000 to $345,000. The net present values of these reductions are presented in Table 12.

This analysis does not include all the categories of benefits that may accrue to the utility. It includes extension of capital for pipes and limited changes in O&M costs. It does not fully incorporate all the potential changes in expenses bearing upon O&M costs, for instance, reduced pumping and energy costs from fewer leaks, decreased water

loss, etc. Therefore, these estimates of distribution system benefits probably undervalue such benefits and actual benefits may be higher.

For comparison, an earlier analysis addressed this issue also (30). That study, conducted 10 years ago, focussed on the costs of damage from internal corrosion in the city of Seattle, Washington. Ryder estimated that efforts by the Seattle Water Department to repair damage from internal corrosion cost the utility about $700,000 per year (1988 dollars), of which 20-30% was avoidable through water treatment.

Two additional categories of potential benefits accrue to the water utility, the consumer and/or society: reduced wasting of water by flushing (which also benefits the sewer utility) and reduced use of bottled water or water purifiers. In public education messages from the EPA intended to reduce exposure to lead in drinking water, the Agency recommended that consumers flush their systems if the water has been sitting all day or overnight. EPA estimates that this consumes 1-2 gallons of water. This may be a low estimate. At a minimum, in households where only 1 parent works, this can account for the wasting of 400 gallons per household per year. The best estimates by the authors of this paper is that the incremental cost of finished water ranges from about 50¢/1000 gallons for large systems to $2 or greater/1000 gallons for small utilities. More realistic assumptions, accounting for the fact that almost 60% of women aged 16-55 are in the labor force (and, hence, out of the home, resulting in 2 "flushes" per day) and that flushing a faucet for 2-4 minutes uses 2-4 gallons of water, would raise the predicted wastage of water to 1,000 - 1,500 gallons per household per year. Reducing this water loss would benefit the utility, the consumer, and society.

Bottled water costs between 70¢ and $3 per gallon, depending upon the brand and the method of delivery. Water purifiers and other point-of-use devices cost from $15 and $600, plus maintenance costs, such as replacement filters, and in some cases electricity. If consumers purchase bottled water or home water devices because of concern for contamination from corrosion by-products, this is a "cost" of corrosion damage. Reducing the number of consumers purchasing bottled water or home water treatment devices will produce an economic benefit to the consumers and society and a "good will" benefit to the utility and is a benefit of the corrosion control treatment.

Of course, consumers also benefit from all the savings experienced by the water utility in the form of reduced bills.

Benefits to Consumers

Public water systems provide water to residential, commercial and industrial users, all of whom would derive benefits from reduced corrosion damage. The nature of benefits to consumers differs from

those that would accrue to the distribution system. These include categories such as extension of useful life of private plumbing and components, reduced repairs, reduced damage from water leaks, reduced aesthetic damages such as staining of fixtures, clothes, etc., and, of course, reduced health effects. Only 1 category of benefits -- reduced damage to residential plumbing systems – is included here. These estimates should be understood as incomplete and partial and are only presented as an indication of the magnitude of total investment and expenditures that can be affected by water treatment to control corrosion. In addition, there is tremendous house to house variation as well as system to system. These per household estimates are averages of estimated benefits; benefits accruing to a specific building will vary.

An effort currently underway for the American Water Works Association Research Foundation is also assembling some data on the potential benefits to consumers for corrosion control (18). Table 13 presents some of the data they have collected. They found that the benefits to consumers from corrosion control exceeded the costs by a factor of 11.4.

The Ryder paper, discussed previously, also evaluated the costs of corrosion damage to residential plumbing in the city of Seattle (30). He found that damage to homes with galvanized plumbing (he did not calculate damage to copper pipes) cost Seattle homeowners about $3.4 million annually; he also did not include damage to other plumbing components, labor costs, etc. Ryder presented a benefit:cost ratio of about 5:1 for consumers alone.

Another earlier study included a similar (and similarly incomplete) assessment of potential benefits to consumers from reductions in damages to private plumbing systems (17). Using a "typical" situation, Kirmeyer and Logsdon found that corrosion control could produce net present value benefits of about $330 per unit (1988 dollars) over the remaining life of the residential plumbing. This is also an underestimate; it includes only damage to pipes, not hot water heaters, faucets, radiators, etc. nor does it include labor costs for the plumber (or time spent by the homeowner).

Our estimates of potential savings to consumers, presented in Table 14, include only incrementally decreased damage to hot water heaters and the extension of service life for residential pipes. Obviously, plumbers are called more often for leaky faucets than to replace the entire plumbing system and corrosivity also affects the rate at which faucets begin to leak (or radiator valves, etc.), so similar cost savings are likely in other categories also. Of course, because only 2 categories have been included in the calculations, these estimates should be seen as lower bounds of the consumer benefits of corrosion control.

Lower Bound Estimates of Benefit: Cost Ratios

Combining our cost and benefit estimates to both utilities and consumers, we estimate the lower bound benefit:cost ratios presented in Table 15 (for lime treatment) and Table 16 (for zinc orthophosphate). We consider these lower bound estimates because they are extremely conservative: the costs are somewhat overestimated and the benefits are significantly underestimated.

As can be seen, centralized installation of treatment to control internal corrosion generally presents positive (and high) benefit:cost ratios across a broad range of plant sizes, chemical approaches and dosages, and treatment success expectations, even when subjected to a rigorously conservative methodology. Under "real world conditions", the authors of this paper estimate that the results could be several factors higher than the results presented here.

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Table 1 - Commonly Available Treatment Chemicals for Controlling Internal Corrosion

Chemical	Form *	Materials	Function
Lime	S	any	pH, hardness adjustment
Hydrated Lime	S	any	pH, hardness adjustment
Caustic Soda	L	any	pH adjustment
Sodium Bicarbonate	S	any	pH, DIC adjustment
Soda Ash	S	any	pH, DIC adjustment
Zinc Orthophosphate	L or S	Fe,Pb,Zn,A-C,Cu?, brass	Forms passivating film
"Generic" Ortho-phosphates	S	Pb,Zn,Fe?,Cu?, brass	Forms passivating film
Phosphoric Acid	L	Pb,Zn,Fe,Cu, brass	Forms passivating film
Hexametaphosphate	S	Fe	Sequestration **
Tripolyphosphate	S	Fe	Sequestration **
Bimetallic poly-phosphate	L or S	Fe	Sequestration **
Silicates	L	Zn,Cu,Fe,Pb?,A-C	Forms film with existing deposits
Limestone	S	any	Raise pH,DIC,hardness of acidic soft waters
Zinc chloride	S	A-C	Forms protective film

* L = liquid; S = solid.
** may form films on some other materials after reversion to orthophosphate

Table 2 - Impacts of Different Common Treatment Chemicals on Some Water Chemistry Variables Relating to Corrosivity *

Chemical	pH	Alkalinity	DIC	Calcium Hardness
Lime	+	+	0	+
Slaked or Hydrated Lime	+	+	0	+
Caustic Soda	+	+	0	0
Sodium Bicarbonate	+ or -	+	+	0
Soda Ash	+	+	+	0
Zinc orthophosphate	-	-	0	0
Phosphoric acid	-	-	0	0
Trisodium orthophosphate	+	+	0	0
Disodium orthophosphate	+ or -	+ or -	0	0
Monosodium orphophosphate	+ or -	+ or -	0	0
Sodium silicates	+	+	0	0
Bimetallic polyphosphates	-	-	0	0(-)**

*Sign indicates direction of change. Some can be either positive or negative depending on dosages and water characteristics
**Creates an "effective" decrease by sequestration or calcium carbonate crystal growth inhibition

Table 3 - Summary of Annualized Costs for pH and Alkalinity Adjustment Using Lime Addition

	DOSAGE					
Plant Size	5 mg/l		10 mg/l		15 mg/l	
1MGD	$/yr	¢/1000 gal	$/yr.	¢/1000 gal	$/yr	¢/1000 gal
Capital Cost*	3,800	1.05	3,800	1.05	3,800	1.05
O&M Costs**	4,100	1.12	4,700	1.29	5,300	1.45
Total Annualized	7,900	2.17	8,500	2.34	9,100	2.49
10 MGD						
Capital Cost*	5,200	0.14	7,000	0.19	10,000	0.27
O&M Costs**	11,000	0.30	20,000	0.55	30,000	0.82
Total Annualized	16,200	0.44	27,000	0.74	40,000	1.09
100 MGD						
Capital Cost*	14,000	0.04	19,000	0.05	19,000	0.05
O&M Costs**	81,000	0.22	128,000	0.35	217,000	0.59
Total Annualized	95,900	0.26	147,000	0.40	236,000	0.64

*Capital costs amortized over 20 years at 6%
**Includes chemical costs.

Table 4 - Summary of Annualized Costs for Addition of Zinc Orthophosphate as a Corrosion Inhibitor

Plant Size	DOSAGE 0.5 mg/l		3 mg/l		5 mg/l	
	$/yr	¢/1000 gal	$/yr	¢/1000 gal	$/yr	¢/1000 gal
1 MGD						
Capital Cost*	3,900	1.07	3,900	1.07	3,900	1.07
O&M Costs**	7,500	2.05	27,000	7.39	42,500	11.64
Total Annualized	11,400	3.12	30,900	8.46	46,400	12.71
10 MGD						
Capital Cost*	3,900	0.11	4,300	0.11	5,000	0.14
O&M Costs**	42,500	1.16	240,000	6.58	397,000	10.88
Total Annualized	46,400	1.27	244,300	6.69	402,000	11.02
100 MGD						
Capital Cost*	5,000	0.01	12,100	0.03	12,000	0.03
O&M Costs**	397,000	1.09	2,365,000	6.48	3,957,000	10.80
Total Annualized	402,000	1.10	2,377,100	6.51	3,969,000	10.83

*Capital costs amortized over 20 years at 6%
**Includes chemical costs

Table 5 - Present Value Estimates for Lime Treatment (thousands of 1988 dollars)

System Size (MGD)	Dosage 5 mg/l	10 mg/l	15 mg/l
1	91	98	105
10	186	309	459
100	1,089	1,688	2,709

Table 6 - Present Value Estimates for Zinc Orthophosphate Treatment (thousands of 1988 dollars)

System Size (MGD)	Dosage 0.5 mg/l	3 mg/l	5 mg/l
1	131	354	532
10	532	2,802	4,611
100	4,611	27,265	45,522

TABLE 7 - Estimates of Annual Per Capita Corrosion Damage (1985 dollars)

Studies	Estimated Annual Corrosion Damage (per capita)			Corrosion Damage Avoidable Through Water Treatment	Annual Per Capita Benefits of Corrosion Control	Assumptions/Notes
	Distribution System	Residential	Total			
Fennelly Engineers (1977)	$5.57	—	$16.71*	30%*	$5.01*	Assumed 30% potential reduction in corrosion damage and that distribution costs were one-third of total costs.
Hudson & Gilcrease (1976)	$8.66*	—	$26.04*	50%	$13.02*	They did not include increased operating costs. Per capita estimate assumes 200 million people are served by public water systems. Assumed that distribution costs were one-third of total costs.
Fennelly Engineers (1978)	—	$30.67*	$46.30*	20%	$9.26*	They calculated $6.17 per capita in savings to residence owners. Assumed residential costs were two-thirds of total costs.
Bennett et al. (1979) (cited in Ryder, 1980)	$9.40	—	$28.20*	22%	$5.64*	Assumed that 200 million people are served by public water systems and that distribution costs were one-third of total costs.
Energy & Environmental Analysis (1979)	$3.98	$7.57	$11.95	38%	$4.54	This is an admitted underestimate it includes only damage to pipes (not damage to water heaters, increased operating costs, etc.)
Ryder (1980)	$1.17	$22.15	$23.36	25%	$5.84	Ryder ascribed 95% of corrosion damage to private owners.
Kimmper & Logsdon (1983)	—	$22.50*	$55.00*	40%	$14.16*	Assumed residential costs were two-thirds of total damage.
					WRAGE $8.21 WOUT EPA $9.62	

* These estimates have been calculated by the authors of this paper. Assumptions are noted above.

Source: US EPA, 1986

Table 8 - Percentage of Annual Costs to Water Utilities by Category

	Support Services	Acquisition	Treatment	Power and Plumbing	Transmission & Distribution
Operating Costs	31	22	12	16	19
Capital Cost	10	13	10		67

Table 9 - Repair Rate Comparison for Selected Utilities

Utility	Miles of Pipe in System	Time Period	Average Number of Repairs per Year	Average Annual Repair Rate (per 100 mi)	Annual Growth Rate (%)
Denver, CO	2,200	1976-83	220	10.8	0
East Bay CA	3,500	1973-82	900	25.9	-4.0
Kenosha, WI	300	1974-82	100	35.6	3.4
Louisville, KY	2,600	1963-83	430	23.7	3.7
Philadelphia PA	3,300	1964-80	880	26.9	1.8
New York, NY	6,100	1970-78	460	7.9	1.5

Table 10 - Estimated Total Capital Investment, and Annualized Capital and Average O&M Costs for Distribution Systems (thousands of 1988 dollars)

Plant Size	Total Capital Investment	Annualized Capital	Annual O&M	Total Annual Costs
1 MGD	$ 4,000	$ 250	$ 93	$ 347
10 MGD	31,200	2,000	610	2,591
100 MGD	242,000	15,400	4,000	19,381

Table 11 - Changes in Total Annual Costs for Distribution Systems from Extended Service Life and Reduced O&M (thousands of 1988 dollars)

% Extension of System Life	Amortization Period (years)	1 MGD	10 MGD	100 MGD
0	50	$347	$2,591	$19,381
5	52.5	345	2,576	19,262
10	55	343	2,563	19,161
15	57.5	342	2,552	19,074
20	60	341	2,542	19,000
25	62.5	339	2,534	18,937
30	65	339	2,527	18,883
35	67.5	338	2,521	18,836
40	70	337	2,516	18,796

Table 12 - Present Value Estimates of Reductions in Annual Distribution Costs (thousands of 1988 dollars)

% Extension of System Life	1 MGD	10 MGD	100 MGD
5	$ 31	$ 241	$ 1,872
10	57	447	3,467
15	80	622	4,829
20	99	772	5,994
25	115	901	6,991
30	129	1,011	7,847
35	142	1,106	8,582
40	152	1,187	9,213

Table 13 - Average Lifetime and Associated Costs for Selected Components of Consumers' Plumbing Systems

	Average	Range
Life of copper piping	49 years	20-100 years
Life of galvanized piping	28 years	15-45 years
Cost of replace accessible plumbing in single family dwelling	$3200	$375-11,000
Life of water heater	12 years	7-25 years
Cost to replace hot water heater	$ 330	$225-500

Table 14 - Annual Costs for Household Plumbing from Extended Service Life

% Extension of Service Life	Amortization Period (years) Household Piping	Hot Water Heater	System Size 1MGD	10MGD	100MGD
			(thousands of 1988 dollars)		
0	49	12.0	$810	$8,102	$81,020
5	51.5	12.6	800	8,004	80,042
10	53.9	13.2	792	7,919	79,185
15	56.4	13.8	784	7,843	78,431
20	58.8	14.4	778	7,776	77,765
25	61.3	15.0	772	7,717	77,174
30	63.7	15.6	766	7,665	76,649
35	66.2	16.2	762	7,618	76,181
40	68.6	16.8	758	7,576	75,761

Table 15 - Lower Bound Benefit:Cost Ratio for Lime Treatment* (1988 dollar benefits:1988 dollar costs)

% Extension	5 mg/l 1 MGD	10 MGD	100 MGD	10 mg/l 1 MGD	10 MGD	100 MGD	15 mg/l 1 MGD	10 MGD	100 MGD
5	1.7	7.9	12.9	1.6	4.7	8.3	1.5	3.2	5.2
10	3.1	14.7	24.1	2.9	8.9	15.6	2.7	5.9	9.7
15	4.4	20.6	33.9	4.1	12.4	21.9	3.8	8.3	13.6
20	5.5	25.7	42.4	5.1	15.5	27.3	4.8	10.4	17.0
25	6.5	30.3	49.8	6.0	18.2	32.1	5.6	12.3	20.0
30	7.3	34.2	56.4	6.8	20.6	36.4	6.3	13.9	22.7
35	8.0	37.7	62.1	7.5	22.7	40.1	7.0	15.3	25.0
40	8.7	40.7	67.2	8.1	24.5	43.3	7.6	16.5	27.0

* Includes both utility and home owner benefits

Table 16 - Lower Bound Benefit:Cost Ratios for Zinc Orthophosphate* (1988 dollar benefits:1988 dollar costs)

% Extension	0.5 mg/l 1 MGD	10 MGD	100 MGD	3 mg/l 1 MGD	10 MGD	100 MGD	5 mg/l 1 MGD	10 MGD	100 MGD
5	1.2	2.8	3.2	0.43	0.5	0.5	0.3	0.3	0.3
10	2.2	5.1	5.7	0.81	1.0	1.0	0.6	0.6	0.5
15	3.1	7.2	8.0	1.1	1.4	1.4	0.8	0.8	0.8
20	3.8	9.0	10.0	1.4	1.7	1.7	0.9	1.0	1.0
25	4.5	10.6	11.8	1.7	2.0	2.0	1.1	1.2	1.2
30	5.1	11.9	13.3	1.9	2.3	2.3	1.3	1.4	1.4
35	5.6	13.2	14.7	2.1	2.5	2.5	1.4	1.5	1.5
40	6.1	14.2	15.9	2.2	2.7	2.7	1.5	1.6	1.6

* Includes both utility and home owner benefits

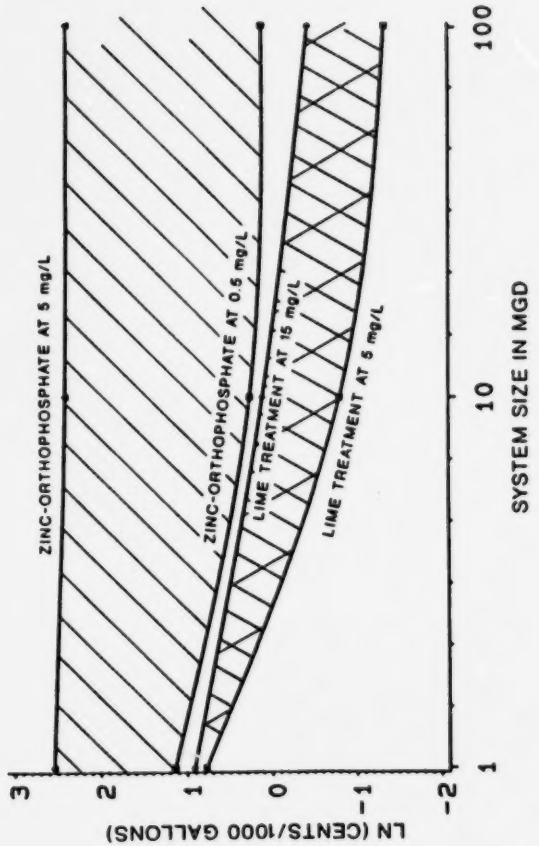

Figure 1 - Unit Cost of Corrosion Control vs. System Size

A SIMULATED DISTRIBUTION SYSTEM DISINFECTION BY-PRODUCT METHOD

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INTRODUCTION

The Metropolitan Water District of Southern California (Metropolitan), a public and municipal corporation of the State of California, provides water as a wholesaler, through its 27 member agencies, to nearly 14.7 million people in a six-county area of Southern California. Metropolitan uses two source waters in its system: Colorado River water (CRW), which travels 242 mi (390 km) from the Colorado River to Metropolitan's 5,100-sq-mi (13,200-km^2) service area, and California State project water (SPW), which travels 444 mi (715 km) from Northern California's Sacramento/San Joaquin Delta via the State Water Project system to Metropolitan's service area. Metropolitan has five treatment plants, with a current maximum sustained capacity of 1.8 billion gallons (6.8 billion litres) per day. At the filtration plants, water is treated by coagulation/flocculation, sedimentation, and dual-media filtration. Disinfection is accomplished by (1) the use of free chlorine through the filtration process for disinfection and to control fishy/swampy taste-and-odor problems and (2) ammonia addition at the filter effluent to form a chloramine residual for trihalomethane (THM) control in the distribution system.

The 1986 amendments to the Safe Drinking Water Act list several disinfection by-products (DBPs) for regulation by the year 1991.[1] The U.S. Environmental Protection Agency (USEPA) is also planning to lower the current maximum contaminant level for THMs. The simulated distribution system (SDS) DBP method that is presented in this paper can be adapted by a utility to evaluate and predict DBP formation in its distribution system and has been used by Metropolitan to evaluate treatment techniques to meet future DBP regulations.

BACKGROUND

THM precursors, which are naturally present in many raw waters, react with free chlorine to form THMs. In addition to THMs, haloacetic acids (HAAs), haloacetonitriles (HANs), haloketones (HKs), chloropicrin, chloral hydrate, and cyanogen chloride have all been identified as chlorination DBPs.[2,3] The THMs and other halogenated DBPs form from the reaction of naturally occurring humic and fulvic substances with free chlorine during disinfection. The SDS THM method was developed to estimate the amount of THMs that form in a distribution system when free chlorine is used as a disinfectant.[4] That method has been modified and is now also